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LOW-LUMINOSITY AGN AS ANALOGUES OF GALACTIC BLACK HOLES IN THE LOW/HARD STATE: EVIDENCE FROM X-RAY TIMING OF NGC 4258

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ABSTRACT

We present a broadband power spectral density function (PSD) measured from extensive *RXTE* monitoring data of the low-luminosity AGN NGC 4258, which has an accurate, maser-determined black hole mass of $(3.9 \pm 0.1) \times 10^7$ $M_\odot$. We constrain the PSD break time scale to be greater than 4.5 d at >90% confidence, which appears to rule out the possibility that NGC 4258 is an analogue of black hole X-ray binaries (BHXRBs) in the high/soft state. In this sense, the PSD of NGC 4258 is different to that of some more-luminous Seyferts, which appear similar to the PSDs of high/soft state X-ray binaries. This result supports previous analogies between LLAGN and X-ray binaries in the low/hard state based on spectral energy distributions, indicating that the AGN/BHXRB analogy is valid across a broad range of accretion rates.

1. INTRODUCTION

The aperiodic X-ray variability in Seyfert Active Galactic Nuclei (AGN) has been well-quantified over multiple time scales. Seyfert broadband fluctuation power spectral density functions (PSDs) show characteristic breaks at temporal frequencies corresponding to time-scales of a few days or less (Uttley, McHardy & Papadakis 2002, Markowitz et al. 2003, McHardy et al. 2004). Markowitz et al. (2003) and McHardy et al. (2004) have shown that the PSD break time-scales measured so far are consistent with scaling roughly linearly with black hole mass $M_{\rm BH}$. Remarkably, the mass–time-scale relation is consistent with extrapolation to stellar-mass black hole X-ray binaries (BHXRBs), and AGN and BHXRB broadband PSD shapes are similar, suggesting that a similar variability process is at work over at least 6 decades in black hole mass.

In BHXRBs the PSD shape and characteristic break time-scales are known to correlate with the X-ray spectral state, which is thought to depend on the global accretion rate relative to Eddington, $L/L_{\rm Edd}$ (e.g. see reviews by McClintock & Remillard 2003, van der Klis 2004). In general, shorter characteristic time-scales are correlated with steeper X-ray power-law components and stronger thermal emission and reflection components, which suggests a model where the inner edge of the accretion disk moves inwards at higher accretion rates and hence characteristic time-scales become shorter (e.g. Gilfanov, Churazov & Revnivtsev 1999). The difference in characteristic time-scales is clear when comparing the PSDs of the low/hard spectral state, in which PSD breaks appear at a few Hz, with the high/soft state, where a similar steepening occurs at higher frequencies > 10 Hz (e.g. Churazov, Gilfanov & Revnivstev 2001).

Recently, McHardy et al. (2004) noted that higher accretion rate Narrow Line Seyfert 1 (NLS1) AGN appear to have relatively shorter PSD break time-scales for their black hole mass than normal Seyferts (and also appear most similar to the PSDs of BHXRBs in the high/soft state, McHardy et al. 2004, 2005). Since NLS1 are thought to accrete at high rates (Pounds, Done & Osborne 1995), this observation would suggest that characteristic time-scales in AGN follow a similar dependence on accretion rate to those in BHXRBs. However, the accretion rates of AGN with good-quality PSDs measured so far are estimated to be a few per cent of Eddington or greater. Since the low/hard–high/soft state transition in BHXRBs seems to occur at $\sim 2\%$ of Eddington (Maccarone 2003), it is not yet clear whether any AGN observed so far should be in the low/hard state (with the possible exception of NGC 3783, Markowitz et al. 2003). Therefore, in order to better test the analogy with BHXRBs and search for evidence of different states in AGN, it is useful to measure the PSDs of X-ray light curves of AGN accreting at significantly lower rates than the existing sample, which may be analogues of BHXRBs in the low/hard state.

In this Letter, we make a first step towards measuring a high-quality PSD for a low-accretion rate AGN, by measuring a preliminary PSD for the LLAGN NGC 4258 ($L/L_{\rm Edd}{\sim}10^{-4}$, e.g., Lasota et al. 1996), using monitoring data obtained in 1997–2000 by the *Rossi X-ray Timing Explorer* (*RXTE*). NGC 4258's black hole mass of $(3.9 \pm 0.1) \times 10^7$ $M_\odot$ is highly accurately measured via VLBI studies of its water megamaser (Miyoshi et al. 1995, Herrnstein et al. 1999), allowing us to make an accurate comparison with the PSD expected from both high/soft and low/hard accretion states.

2. OBSERVATIONS AND DATA REDUCTION

We constructed a high-dynamic-range PSD for NGC 4258 by combining monitoring on complementary time scales (e.g., Edelson & Nandra 1999). NGC 4258 was monitored regularly once every 2–3 days by *RXTE* from 1997 Dec 27 to 2000 Mar 1 ("long-term" monitoring). Each visit lasted ~1 ksec. There was also intensive, simultaneous *RXTE* and *ASCA* monitoring during 2000 May 15–20, when the source was observed every orbit ("short-term" monitoring). For consistency we only use

the short-term *RXTE* PCA data here, binned to 5760 s (i.e. single orbit) intervals, but note that the 2-10 keV *ASCA* short-term light curve is consistent with the *RXTE* light curve. Data were obtained from *RXTE*'s proportional counter array (PCA), using standard extraction methods and selection criteria appropriate for faint sources (see Markowitz et al. (2003) for further details). Light curves were generated over the 2–10 keV bandpass. All count rates quoted herein are normalized to 1 proportional counter unit (PCU). The light curves are plotted in Figure 1. One can see that NGC 4258 displays minimal variability on short time scales; other observations (e.g., Pietsch & Read 2002) also show minimal variability on $\lesssim$day time scales. In contrast, there is strong variability on long time scales. The fractional variability amplitude F_{var}, as defined in e.g., Vaughan et al. (2003), is 4.2 $\pm$ 0.8 % and 27.9 $\pm$ 0.2 % for the short- and long-term light curves, respectively[3].

The 2–10 keV X-ray emission is dominated by the direct nuclear emission in this source (e.g., Fiore et al. 2001). Variability due solely to variations in the intrinsic column density is negligible, as the column density is not strongly variable, even on time scales of years (Risaliti, Elvis & Nicastro 2002). Furthermore, a plot of the binned 2–4 keV flux versus the 7–10 keV flux (which, for brevity, we do not show here) shows a continuous, virtually linear distribution of points, suggesting a lack of strong absorption events during the monitoring.

3. THE PSD OF NGC 4258

3.1. *Constraints on PSD break time-scale*

We used the PSRESP Monte Carlo method of Uttley et al. 2002 (and see Markowitz et al. 2003) to constrain the shape of the PSD. Monte Carlo simulations are required to take account of aliasing effects due to sparse and/or irregular sampling, which distorts the PSD shape. Furthermore, simulations are essential to properly determine confidence limits and goodness of fit of models while using the full dynamic range of the PSD, since the lowest frequencies in the PSDs of the long and short-term light curves are not well-sampled enough to allow standard, Gaussian errors to be assigned to the PSD. The method is fully described in Uttley et al. (2002), Markowitz et al. (2003) and see also M^{c}Hardy (2004)[4]. The long- and short-term PSDs spanned the temporal frequency ranges 2×10^{-8}–3×10^{-7} Hz and 4×10^{-6}–9×10^{-5} Hz respectively. The power due to Poisson noise over the 2–10 keV bandpass was 860 Hz^{-1} and 8.3 Hz^{-1} for the long- and short-term PSDs, respectively.

To constrain the location of any PSD break, we employed a broken power law model of the form $P(f) = A(f/f_c)^{-1}, f \leq f_c$, and $P(f) = A(f/f_c)^{-\beta}, f > f_c$, where the normalization A is the PSD amplitude at the break frequency f_c, β is the high frequency power law slope, with the constraint $\beta > 1$. This simple model provides a good description of the PSDs of Seyfert galaxies measured so far, with PSD breaks detected in 8 of those AGN. The range of β tested was 1.0–2.3 in increments of 0.1. Break frequencies were tested from 10^{-8}–10^{-5} Hz, in multiplicative steps of 1.5. The best-fitting model is one with a break at 2.25×10^{-8} Hz, although an unbroken power-law is also formally acceptable (i.e. the break frequency could lie out of the observed range). The best-fitting $\beta = 2.3$, $A = (3.3\pm^{1.3}_{0.9}) \times 10^6$ Hz^{-1}, and the "rejection probability" (corresponding to the fraction of simulated PSD sets which are a better fit to the assumed model than the real data) is 0.43, i.e. the model is formally acceptable. Contour plots showing the rejection probabilities for a given β and f_c are shown in Figure 2. On the contour plot we also show the expected break frequencies assuming linear scaling with mass from typical values of break time-scale in the low/hard and high/soft states of the BHXRB Cyg X-1 (assuming a 10 $M_\odot$ black hole in Cyg X-1, e.g., Herrero et al. 1995, and the well-determined maser mass of $(3.9 \pm 0.1) \times 10^7$ $M_\odot$ in NGC 4258). The high/soft state break frequency (corresponding to 4.5 d) is ruled out at >90% confidence, while the low/hard state break (~45 d) is acceptable at this level of confidence.

Fiore et al. (2001) report a 1998 December *BeppoSAX* 3-10 keV light curve of NGC 4258 which shows almost a factor 2 change in flux in one day. This behavior is atypical of the source, which shows much smaller variations on time-scales of a few days in both the *RXTE* long-term monitoring and the much more intensive monitoring. We investigated whether this relatively large variation in the *BeppoSAX* observation was consistent with the PSD derived from *RXTE* monitoring, by including the *BeppoSAX* light curve (obtained directly from the public archive) in our fits. We find that the rejection probability for the broken power-law PSD is increased to 0.77, but the overall confidence contours for f_c and β are only made marginally wider. We conclude that the *BeppoSAX* light curve is consistent with the *RXTE PSD* and simply represents a statistical outlier in the stochastic variability process.

3.2. *Comparison with other AGN*

The PSD of the LLAGN NGC 4258 does indeed appear to be better explained by scaling from a low/hard state PSD than from a high/soft state PSD, *unlike* the PSDs of some of the Seyfert galaxies measured so far which rule out a low/hard state interpretation and are consistent with a high/soft state interpretation (e.g. NGC 4051, MCG-6-30-15, M^{c}Hardy et al. 2004, 2005; NGC 3227, Uttley & M^{c}Hardy 2005). To demonstrate this difference in the PSDs, we show in Figure 3 a relatively model-independent comparison between the PSD of NGC 4258 and that of a normal Seyfert with nearly identical black hole mass, NGC 3516 ($M_{\rm BH} = 4.3\pm1.5\times10^7 M_\odot$, Peterson et al. 2004), together with the PSDs of Cyg X-1 in low/hard and high/soft states for further comparison. NGC 3516's accretion rate is likely ~5% of Eddington, given its 2–10 keV luminosity of 10^{43} erg s^{-1} and assuming the X-ray-to-bolometric luminosity scaling of Padovani & Rafanelli (1988). Within the errors, the PSD break time-scale of NGC 3516 is more consistent with linearly scaling

[3] The errors on F_{var} account for observational noise only, not intrinsic stochastic variability.

[4] We note here that to improve S/N, the long-term light curve was binned up in 2-week intervals. Model fits were carried out using grids of PSD model parameter values, and at each point in the grid 400 simulated light curves were generated for each light curve (long and short-term), resampled to match the sampling of the observed light curves (and rebinned to 2-week bins in the case of the long-term simulated data) and 4000 combinations of the resulting simulated PSDs were used to estimate the goodness of fit for that set of model parameters.

from the high-frequency break of Cyg X-1 in the high/soft state, though scaling from the low/hard state cannot be ruled out. From the figure, although its amplitude at low frequencies is similar to that of NGC 3516, NGC 4258's PSD is consistent with being shifted downward in temporal frequency by a factor of $\sim$100 relative to NGC 3516's PSD. Given the similarity in black hole mass between the two objects and the overlapping temporal-frequency range of the PSDs, the fact that a PSD break was unambiguously detected in the PSD of NGC 3516 but not in the that of NGC 4258 reinforces this notion. Furthermore, the fact that NGC 4258 shows similar levels of long-time scale variability to normal Seyferts of comparable mass ($F_{var} \sim$ 30%, Markowitz & Edelson 2004) rules out the possibility that the normalization of NGC 4258's PSD is significantly lower compared to that for normal Seyferts. The PSDs are thus consistent with the notion that for a given mass, a PSD shifted towards relatively lower temporal frequencies is associated with a lower accretion rate. NGC 4258, and by extension, other LLAGN, may thus be a low accretion rate version of normal Seyferts, as far as X-ray continuum variability is concerned.

4. CONCLUSIONS

We have shown that the PSD of NGC 4258 is consistent with having the same shape and normalization as more luminous Seyfert galaxies, but with a break on longer timescales than expected by scaling from the high/soft state of Cyg X-1, unlike a Seyfert galaxy with similar mass, NGC 3516. From a purely phenomenological point of view, this result may help to explain the differences in short-term (<day) variability amplitude between LLAGN and Seyfert galaxies reported by Ptak et al. (1998), who showed that LLAGN do not follow the well known anti-correlation between X-ray luminosity and short-term variability amplitude which is shown by normal Seyferts (e.g., Nandra et al. 1997), but instead populate the low-luminosity, low-variability part of the variance-luminosity diagram. NGC 4258 also shows a very low variability amplitude on short time-scales, and our PSD suggests that this is due to a long break time-scale in this AGN, rather than a low overall normalization of the PSD. The same might also be true of other LLAGN.

The comparison with break-time-scale expected from mass-scaling of the time-scales from Cyg X-1, and the comparison with the PSD of NGC 3516, both suggest that the break time-scale in NGC 4258 is intrinsically longer (given its mass) than in more luminous AGN. This difference may reflect the low accretion rate in NGC 4258. NGC 4258 appears to be consistent with scaling from the low/hard state PSD of Cyg X-1, although it is possible that the break time-scale is even longer than that scaling would suggest. An analogy with other BHXRBs, which display a larger range of $L/L_{\rm Edd}$ than Cyg X-1, supports this possibility. For example in the outburst decays of transient BHXRB candidates, after transition from the high/soft spectral state to the low/hard spectral state, there is evidence that PSD time scales, particularly QPOs, continue to migrate towards lower frequencies as the luminosity and accretion rate of the source decrease and the source approaches quiescence (van der Klis 2004, Kalemci et al. 2004, Rodriguez et al. 2004, Nowak, Wilms & Dove 2002).

Despite the consistency with BHXRB behavior, it is still not clear whether the dependency of the mass–timescale relation on AGN accretion rate is a continuous scaling, or if it exists in the form of a high vs. low accretion rate dichotomy akin to that seen in BHXRBs. However, there are differences in the observed energy-spectral features of LLAGN and normal Seyferts which are suggestive of differing accretion modes in the two classes of objects. Specifically, LLAGN are more radio loud compared to normal Seyferts, and the so-called optical/UV "big blue bump" in normal Seyferts, inferred to be thermal accretion disk emission, is absent in LLAGN (Ho 1999). Similar discrepancies arise when comparing the spectral energy distributions of low/hard and high/soft-state BHXRBs (though in this case, due to the much smaller, hotter disks of BHXRBs, the thermal emission appears in the X-ray band). Nagar et al. (2005) have suggested that both LLAGN and low/hard state BHXRBs are low-efficiency accreting sources, as both classes of objects are often associated with strong radio jet emission and low levels of thermal disk emission. Higher-efficiency accreting sources, namely normal Seyferts and high/soft-state BHXRBs, meanwhile, usually lack strong radio emission but have a strong disk signature, with the supermassive systems also having gas-rich nuclei. Additionally, a fundamental plane between $M_{\rm BH}$ and X-ray and radio luminosities is seen in both stellar-mass and supermassive systems (Merloni, Heinz & di Matteo 2003; Falcke, Körding & Markoff 2004). However, this relation breaks down for high-state objects; radio power is reduced e.g., for high/soft state BHXRBs and normal Seyferts (Gallo, Fender & Pooley 2003; Maccarone, Gallo & Fender 2003), further supporting the notion of a similar dichotomy of states for AGN and BHXRBs. Finally, based on the distributions of $M_{\rm BH}$ and bolometric luminosities, Jester (2005) has suggested that in AGN, there is tentative evidence for the existence of a critical accretion rate, $L/L_{\rm Edd} \sim$ 0.01, which separates high- and low-efficiency accretion modes. The number of low-efficiency accreting sources in that sample was small, but all were LLAGN.

For LLAGN and low/hard-state BHXRBs, the longer variability time scales for a given mass, reduced emission from the optically thick, radiatively-efficient disk, and relative weakness of Fe Kα emission (e.g., Pietsch & Read 2002; REF FOR XRBs) are all consistent with the suggestion that the inner accretion disk is truncated, possibly existing at smaller radii as an optically thin, radiatively inefficient, advection-dominated accretion flow (ADAF; Narayan & Yi 1995). ADAF models have frequently been invoked to explain the spectral energy distributions in NGC 4258 and other LLAGN (e.g., Yuan et al. 2002). As one example, one popular geometrical model for the accretion configuration is the so-called "sphere + disk" model of Dove et al. (1997) and Esin, McClintock & Narayan (1997). This model features a geometrically-thick, sometimes spherical, ADAF flow, at the innermost radii, surrounded by a radiatively efficient, geometrically thin disk. The transition radius between the ADAF and thin disk appears at relatively larger radii for lower accretion rates. Also, considerations of how an ADAF/coronal accretion flow can form from evaporation of the optically thick disk have suggested that the inner disk may evapo-

rate completely into an optically-thin flow if the accretion rate transitions from above to below a critical accretion rate (Różańska & Czerny 2001; Meyer-Hofmeister & Meyer 2003 and references therein). Further progress in this area can be made by firmly establishing whether such a critical accretion rate exists in AGN and if it is indeed responsible for the dominance of high- or low-efficiency accretion modes as a function of accretion rate. Measuring PSD breaks for a larger number of AGN, including LLAGN, is also necessary to critically test the dependence of the mass–time scale relation on accretion rate. Clarification of these issues in AGN as well as in BHXRBs will help to unify the behavior of stellar-mass and supermassive accreting black holes.

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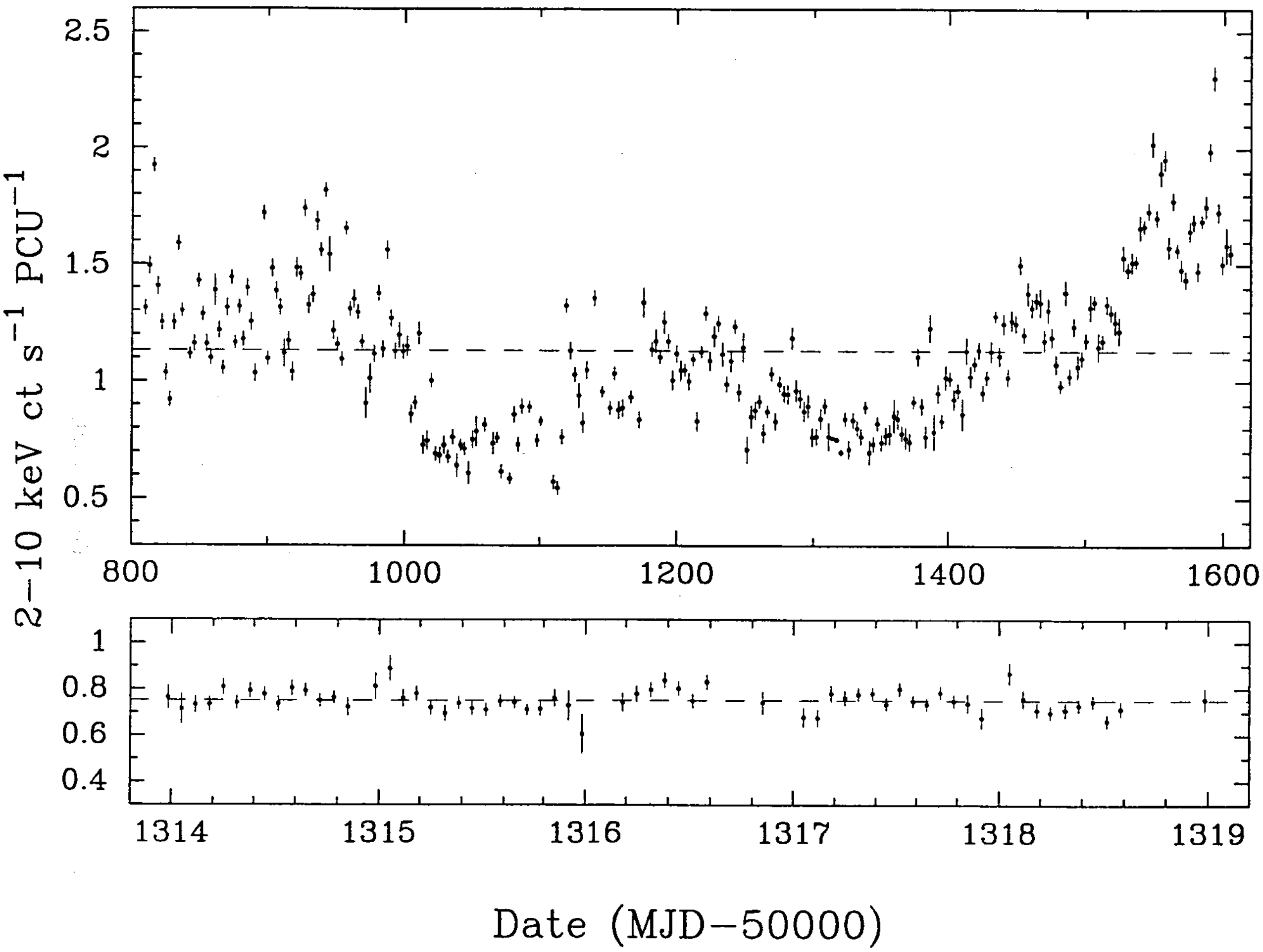

FIG. 1.— 2–10 keV light curves for the long-term (top) and short-term (bottom) monitoring.

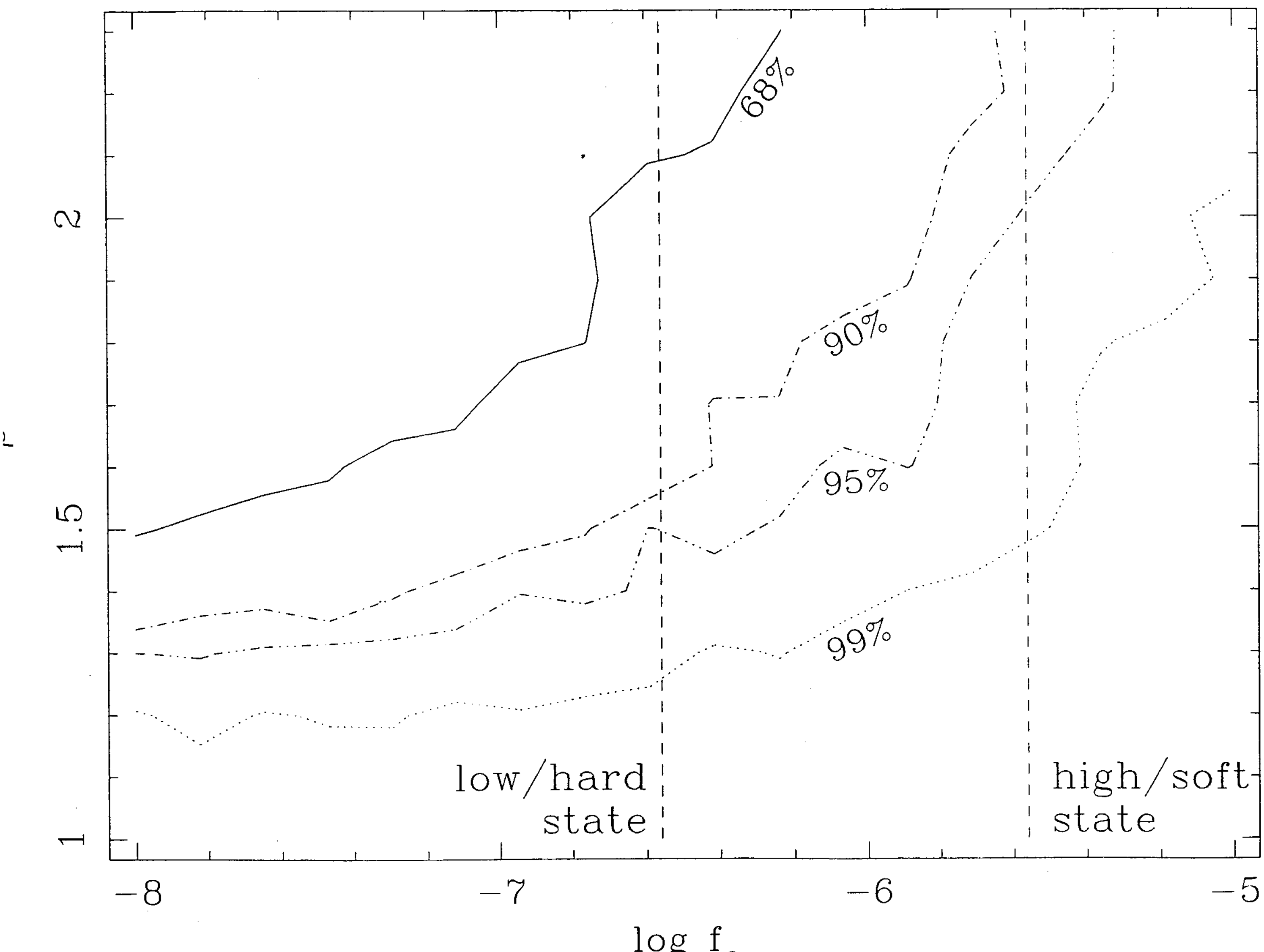

FIG. 2. – Contour plot showing the 68%, 90%, 95% and 99% rejection confidence levels for break frequency f_c versus high-frequency PSD slope β. The vertical dashed lines show the break frequency predictions from linearly scaling from the low/hard and high/soft states of Cyg X-1.

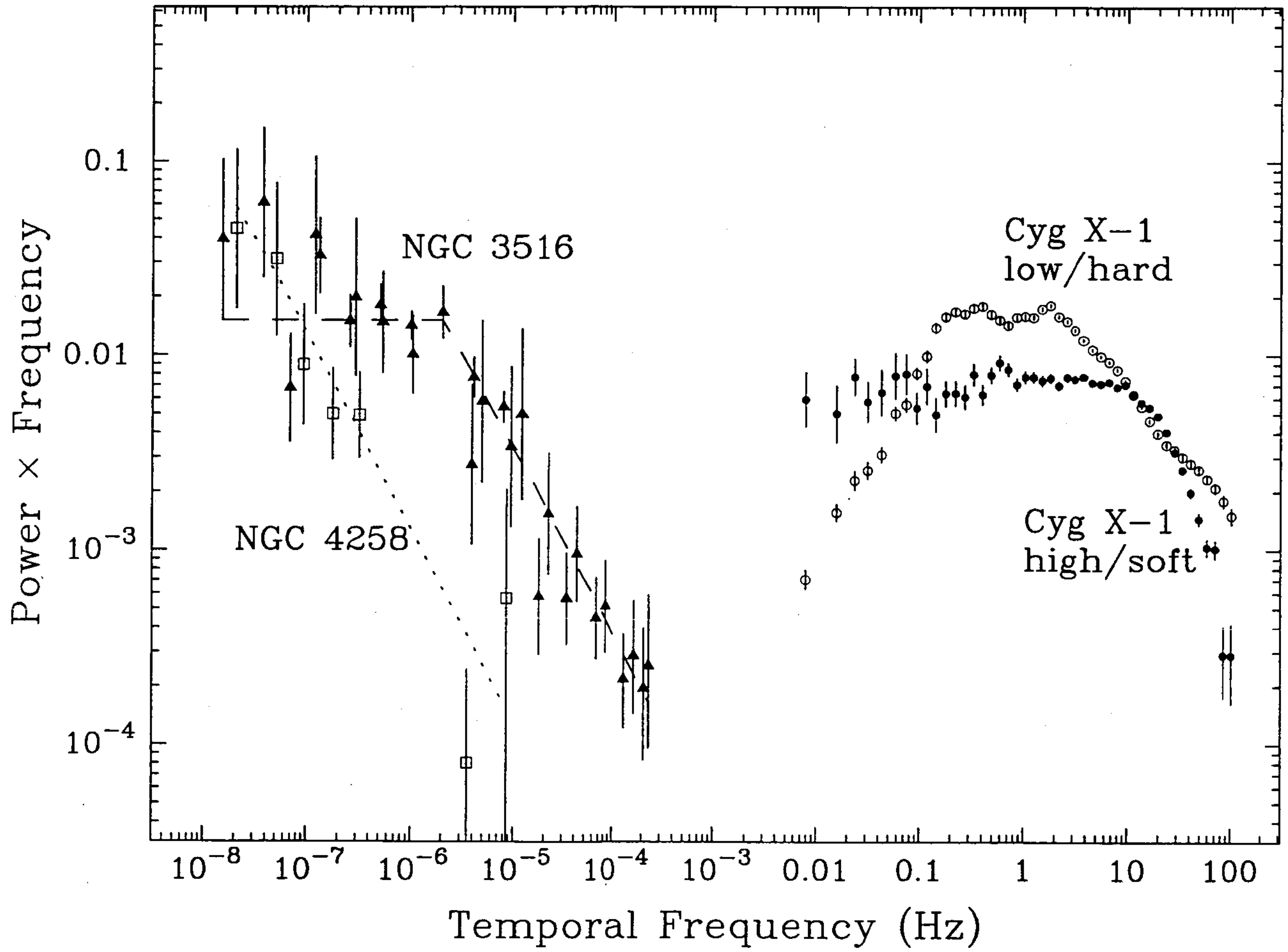

FIG. 3.— PSDs of NGC 4258 and NGC 3516. As discussed in the text, the two AGN have similar black hole masses, but the PSD of the lower accretion rate NGC 4258 is consistent with being scaled to lower temporal frequencies. The five highest-frequency short-term PSD points for NGC 4258 are very poorly constrained because they are close to the Poisson noise level, and are therefore not plotted.